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The Effect of Diet and Sociopolitical Change on the Physiological Stress and Behavior in the Late Roman-Early Byzantine (300-700 AD) and Islamic (902-1235 AD) Populations from Ibiza, Spain

Osipov, Benjamin[1]; Alaica, Aleksa K[2,3]; Pickard, Catriona[3]; Garcia-Donas, Julieta G[4]; Márquez-Grant, Nicholas[5]; Kranioti, Elena F.[3,6]

[1]Lawrence J. Ellison Musculoskeletal Research Center, Department of Orthopaedic Surgery, University of California Davis Medical Center, 4635 2nd Avenue, Suite 2000, Sacramento, CA 95817, USA

[2] Department of Anthropology, University of Toronto, 19 Russell Street, Toronto, Ontario, M5S 2S2, Canada

[3] School of History, Classics and Archaeology, University of Edinburgh, Edinburgh, EH8 9AG, UK

[4] School of Anthropology and Conservation, Marlowe Building, University of Kent, Canterbury, Kent CT2 7NR, Kent, UK

[5]Cranfield Forensic Institute, Cranfield University, Defence Academy of the United Kingdom, SN6 8LA, Shrivenham, UK

[6] Department of Forensic Sciences, Faculty of Medicine, University of Crete, 71110, Heraklion, Crete, Greece

Correspondence:
Benjamin Osipov, Lawrence J. Ellison Musculoskeletal Research Center, Department of Orthopaedic Surgery, University of California Davis Medical Center, 4635 2nd Avenue, Suite 2000, Sacramento, CA 95817, USA
Email: bosipov@ucdavis.edu

Abstract

Objectives

This study evaluated chronological changes in physiological stress and levels of habitual loading of Ibizan populations from the Late Roman-Early Byzantine to the Islamic period (300-1235 AD) using measures of body size and bone cross-sectional properties. It also explored the effect of diet, modeled using stable isotopes, on physiological stress levels and behavior.

Materials and Methods

The sample comprised individuals from three archaeological populations: Urban Late Roman- Early Byzantine (LREB) (300-700 AD), Medieval Urban Islamic (902-1235 AD), and Rural Islamic. Bone lengths, femoral head dimensions, and diaphyseal products and circumferences were compared to assess differences in body size and habitual loading in 222 adult individuals. Ordinary least squares regression evaluated the correlations between these measures and carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$) stable isotope ratios in 115 individuals for whom both isotope values and osteological measures are available.

Results

The Rural Islamic group had shorter stature and reduced lower limb cross-sectional properties compared to the two urban groups. In both LREB and Islamic groups, body mass and femur length was positively correlated with $\delta^{13}C$ values, and $\delta^{15}N$ shows a positive correlation with left humerus shape in the LREB Urban sample.

Conclusions

The low stature and cross-sectional properties of the Rural Islamic group are most likely an indicator of greater physiological stress, potentially due to poorer diet. Positive correlations between measures of body size and $\delta^{13}C$ values further suggest that greater access to C_4 resources improved diet quality. Alternatively, this relationship could indicate greater body size among migrants from areas where individuals consumed more C_4 resources.

Keywords: Stable Isotopes; Bone Functional Adaptation; Behavior; Mediterranean; Dietary Reconstruction, Ibiza

1. Introduction

1.1 Archaeological and Historical Background

The Spanish island of Ibiza, part of the Balearic Islands, is located in the Western Mediterranean. The island has a surface area between 541-570 km^2, and the terrain is rugged (Naval Intelligence Division, 1941; Vallès, 2000 a,b,c). Its location, along major maritime Mediterranean trade routes, made it an important hub for trade and migration since the 8th Century BC (Ruiz de Arbulo, 1991, Aubet 1993, 1995, Moreno, 2003; Garrigós et al., 2004; Albero Santacreu et al., 2019; Zavagno, 2019). The Phoenician period was followed by the Carthaginian or Punic period, which from the 6th century onwards involved deep demographic, economic, religious and cultural transformations to the island (Costa, 2019a). From the 2nd century BC and in particular from the 1st century AD onwards, Ibiza came under the control of Rome (Costa, 2019b). During the Late Antiquity-Early Byzantine period (4th-8th th centuries AD), Roman political control collapsed, Vandals conquered the island from c. 455 until 535 AD, and subsequently the Byzantine Empire asserted control until approximately 700 AD (O'Callaghan, 1983; Collins, 1995; Kulikowski, 2004; Costa, 2019c). Changes came with the arrival of Islam in Iberia in 711, with Islamic influence or exploration extended to Ibiza in the 8th and 9th centuries and a final colonization of Ibiza in 902 AD (O'Callaghan, 1983; Collins, 1995; Garrigós et al., 2004; Zavagno, 2019; Ferrer Abárzuza, 2019a). This colonization of the Balearic Islands in 902 as evidenced in historical texts, appears to have been quick by migration from the Iberian Peninsula or in a small and less likely scale, by an influx from North Africa (Ferrer Abárzuza, 2019a). The end of Islamic rule took place in 1235 AD with the conquest of the island by Christian troops from the Crown of Aragon (Ferrer Abárzuza, 2019b).

Some attention has been given to the effect of the socio-political changes that occurred during these periods on behavior and levels of physiological stress (*e.g.* diet quality, disease load) (e.g. see Márquez-Grant, 1999, 2006) but this still largely remains poorly understood. This study focuses on the relationship between diet, stress, and behavior. Previous isotopic studies of diet have demonstrated diachronic change and inter-individual variability in diet throughout the Late Roman-Early Byzantine (LREB) and the Islamic period (Alexander et al. 2019; Márquez-Grant et al., 2003; Fuller et al., 2010; Nehlich et al., 2012; Pickard et al., 2017; Alaica et al., 2019; Dury et al., 2018). Other lines of evidence also suggest political, economic, and cultural change across these periods (Ramon, 1986; Gurrea and Martín, 2000; Costa, 2019c; Ferrer Abárzuza, 2019a). As on mainland Spain, a number of rural settlements in the Balearic Islands were abandoned in the Late Roman period, suggesting either decrease in population or potentially concentration in more defensible, sites (Florit and Ontiveros, 2011). This is also potentially linked to a decrease in the export of wine and oil (Ramon, 1995). These changes in settlements and in the economy, resulting in a reorganization of the rural landscape, have also been observed especially in the 3rd century AD onwards in a number of sites in Ibiza (Ramón, 1995; González and Pachecho, 2002, Costa, 2019c). The causes of change in settlement patterns remains unclear, but it may represent retreat to more defensible space. Alternatively, a general period of aridity and drought appears to have been present in the Mediterranean in AD 300-400 and AD 800, with maximum temperatures in the fourth century AD (Lamb, 1982). Whether climate change induced crop failure contributed to change in settlement patterns remains unclear, but some reoccupation of rural settlements began in Byzantine times (Ramon 1995; González and Pacheco, 2002). Islamic migrants from Spain in particular, as well as North Africa contributed to the reoccupation of rural areas and introduced new technologies and crops amongst other innovations; there was also considerable diversity in farming methods (Kirchner, 2009; Heiss et al., 2014; Ferrer Abárzuza, 2019a). Despite these considerable social, political, and behavioral transformations, published studies on disease and behavior from skeletal remains in this latter period are lacking with some exceptions (Kyriakou et al., 2012), and data is primarily encountered in dissertations or unpublished reports (e.g. Márquez-Grant, 1999; Camarós i Pérez et al., n,d,; Valli, 2012; Gundersen, n.d.; Tonks, n.d.). One notable study has compared rural Islamic skeletal material to LREB populations and mainland

Spanish medieval samples (Kyriakou et al., 2012). Rural Islamic individuals exhibited lower stature than earlier Ibiza populations and medieval Islamic and Christian groups from mainland Spain. However, the rural Islamic group also showed lower frequencies of cribra orbitalia, an indicator of anemia or other non-specific stress. This study explores how health, workloads, and behavior varied across approximately 1000 years in Ibiza's history by comparing the Late Roman-Early Byzantine (300-700 AD) to the Islamic period (902-1235 AD) using measures of body size and cross-sectional properties. These measures are used because they provide direct evidence of differences in body size and habitual behavior. It also evaluates the relationship between diet, physiological stress, and behavior. This will allow new insights into the history of the Balearic Islands and complement prior archaeological studies.

1.2 Skeletal Studies of Body Size, Physiological Stress, and Behavior

Analysis of body size and bone robusticity provides insight into levels of physiological stress and behavior of past populations. If severe or sustained enough, growth perturbations, such as disease and malnutrition during childhood, stunt appositional growth and accrual of body mass. If deficits are severe or sustained enough to prevent catch-up growth, they result in reduced adult stature, long bone length, and body mass. Variation in stature and bone length has been used extensively to evaluate differences in longitudinal growth reflective of difference in growth stress between populations (Maat, 2005; Saunders, 2008; Mays et al., 2009; Ruff et al., 2013; Lukacs et al., 2014; Temple et al., 2014; Hughes-Morey, 2016; Mays, 2016). Joint surface dimensions allow reconstruction of body mass, as they undergo functional adaptation to the mechanical load imposed by body mass (Trinkaus et al., 1994; Lieberman et al., 2001; Auerbach and Ruff, 2004). As is the case with long bone length, temporal and chronological changes in body mass have been considered indicative of differences in disease load and diet during development (Pfeiffer and Sealy, 2006; Stock et al., 2010, 2011; Auerbach, 2011). Importantly, articular surface dimensions may most closely correspond to body weight at the end of development and not closely track body mass changes in adulthood. In a study of modern individuals, femoral head dimensions exhibited a higher correlation with body weight at the age of 18 years than current body weight (Ruff et al., 1991). Thus, both long bone length and joint dimensions primarily provide information about levels of developmental stress from birth to young adulthood.

Analyzing diaphyseal cross-sectional properties, reinforcement of skeletal elements in a transverse plane to the long axis, allows reconstruction of both the habitual behavior and body size of past populations (Ruff et al., 2006a; Ruff, 2008; Ruff and Larsen, 2014). While joint surfaces primarily adapt to the mechanical loads imposed by body weight, cross-sectional dimensions adapt to withstand habitual loads imposed by both body size and activity (Ruff, 2000; Lieberman et al., 2004). Most studies have used diaphyseal cross-sectional properties to reconstruct behavior (Bridges, 1989; Holt, 2003; Stock and Pfeiffer, 2004; Marchi et al., 2006; Sparacello and Marchi, 2008; Larsen and Ruff, 2011; Lieverse et al., 2011; Stock et al., 2011; Macintosh et al., 2014, 2017; Ruff and Larsen, 2014; May and Ruff, 2016). Lower limb shape and strength have primarily been used to identify differences in levels of terrestrial mobility, because bipedal locomotion creates greater loads in the anteroposterior than the mediolateral plane (Holt, 2003; Stock and Pfeiffer, 2004; Marchi et al., 2006; Sparacello and Marchi, 2008; Shaw and Stock, 2009, 2013; Lieverse et al., 2011). Variation in upper limb shape and strength has been linked to the practice of different subsistence modes and the employment of different technology (Stock and Pfeiffer, 2004; Macintosh et al., 2014; Shackelford, 2014; Cameron et al., 2018).

Furthermore, combining estimates of body mass from diaphyseal cross-sectional properties and joint dimensions may provide a unique perspective on changes in weight throughout life (Pomeroy et al., 2018). Although the greatest changes in both diaphyseal cross-sectional properties and joint dimensions occur during the growth period, diaphyseal cross-sections continue to respond to changes in mechanical loading into later adulthood, albeit at a reduced rate compared to the juvenile period (Ruff et al., 1991; Lieberman et al., 2001). Therefore, it is reasonable to postulate that joint dimension comparisons shed light on body mass differences established by young adulthood, whereas diaphyseal cross-sectional properties may prove more indicative of body mass at time of death (Pomeroy et al., 2018). A small number of studies have used bone robusticity to analyze differences in body mass in both juveniles and adults of past and current populations (Ruff et al., 1991; Cowgill, 2010, 2017; Robbins et al., 2010; Pomeroy et al., 2018). However, since diaphyseal dimensions also adapt to activity induced loading, it has proven difficult to parcel out the extent to which differences in cross-sectional properties between past populations reflect variation in activity level or body mass (Cowgill, 2017).

Lastly, variation in body size and cross-sectional properties can reflect genetic differences between populations. Some proportion of bone cross-sectional properties and bone length is heritable, though the extent of genetic control remains poorly understood (Holliday, 1997; Peacock et al., 2005; Ruff et al., 2006a; Duren et al., 2013; Adams and Ackert-Bicknell, 2015; Roseman and Auerbach, 2015). Joint surfaces and bone length "grow ahead" of body mass, suggesting growth towards genetically canalized endpoint, which may vary between populations being compared (Frisancho et al., 1980; Ruff, 2007; Saunders, 2008; Ruff et al., 2013; Roseman and Auerbach, 2015). Similarly, studies have repeatedly demonstrated that population structure explains a substantial portion of variation in body size between populations (Allen, 1877; Holliday, 1997; Cowgill et al., 2012; Ruff et al., 2012; Roseman and Auerbach, 2015). As Ibiza has been repeatedly colonized throughout its history, the contribution of migration to

Ibiza's genetic history makes this an especially important consideration. The origin of migrants to Ibiza and the extent of their genetic contribution to contemporary Ibiza remain much debated, and a full consideration falls beyond the scope of this analysis (Tomàs et al., 2006; Zalloua et al., 2018; Biagini et al., 2019). Craniometrics may give support to some migration from North and Sub-Saharan Africa since at least the Punic colonization (6th century BC onwards) (Márquez-Grant, 2005, 2006) and genetic discontinuity through time is also supported by recent DNA studies (Biagini et al. 2019). What is clear, is that migration, whether primarily from mainland Spain as well as perhaps a component of North and Sub-Saharan Africa seems to be the scenario for most of Ibiza's archaeological past, as documented not only through biology but also material culture (Kaufman, 2000; Márquez-Grant, 2006; Ferrer, 2019). Overall, a critical analysis of skeletal cross-sectional properties and body size can shed light on chronological variation in the levels of physiological stress, behavior, and genetics of Ibizan populations.

1.3 The Relationship between Diet, Physiological Stress, and Behavior

Stable isotope analysis and historical sources allow reconstruction of diet, facilitating nuanced interpretations of chronological variations in body size and behavior. The stable carbon isotope ratio, $^{13}C/^{12}C$ ($\delta^{13}C$), and stable nitrogen isotope ratio, $^{15}N/^{14}N$ ($\delta^{15}N$), of bone collagen indicate the sources of dietary protein (Chisholm et al., 1982; Sealy, 2001; Katzenberg, 2008; Salazar-García et al., 2014; Pickard et al., 2017). When individuals primarily depend on the terrestrial food web, variation in $\delta^{13}C$ between individuals or populations reflects differences in the proportion of C_3 and C_4 crops in diet, as C_4 crops and animals eating these plants are typically enriched in ^{13}C relative to the C_3 food web. Alternatively, enrichment in $\delta^{13}C$ can result from consumption of marine foods, due to the relative ^{13}C enrichment of inorganic carbon in ocean water in comparison to atmospheric CO_2 (Schoeninger and DeNiro, 1984). Variability in $\delta^{15}N$ arises due to soil values, method of fixing atmospheric N_2, and trophic level fractionation effects. Within a single food chain organisms occupying a higher trophic level have higher $\delta^{15}N$ (Schoeninger and DeNiro, 1984; Katzenberg, 2008). As aquatic food chains are generally longer than terrestrial ones, $\delta^{15}N$ comparisons have been used to distinguish individuals that include marine or freshwater resources in their diet from those that do not (Kusaka et al., 2010).

A central ambiguity in reconstructing diet from bone collagen is that it remains unclear how accurately carbon isotope values reflect dietary energy sources (i.e. lipids and carbohydrates). It has been well established that collagen is, in protein adequate diets, predominantly synthesized from dietary protein (Ambrose and Norr, 1992; Jim et al., 2004, 2006; Katzenberg, 2008; cf. Fernandes et al., 2012). As C_4 crops tend to be high in carbohydrates, collagen carbon values would underestimate their contribution to diet. However, Roman-Medieval/Islamic period Spanish diets were likely dominated by cereals (in particular wheat and barley) and low in protein (Pickard et al., 2017). In this case, nutrient scrambling may occur, resulting in an increased contribution of carbohydrate carbon atoms to the synthesis of non-essential amino acids. Conversely, nitrogen will still derive from dietary protein (Jim et al., 2006; Pickard et al., 2017). This potential scenario must be taken into account when interpreting stable isotope signatures of Ibizan populations. However, variation in nitrogen isotope ratios may also reflect differences in levels of dietary stress (Katzenberg, 2008; Waters-Rist et al., 2011; Trochine et al., 2019).

Evaluating correlations between skeletal dimensions and stable isotope ratios of bone collagen can improve understanding of the relationship between subsistence strategies, body size, behavior, and physiological stress levels. This approach has been previously employed in only a handful of studies (Larsen et al., 2001; Pfeiffer and Sealy, 2006; Suby and Guichón, 2009). These detected correlations between stable isotope signatures, body mass, and bone cross-sectional properties, indicating that such analysis has the potential to provide new insights into the interactions between diet, stress levels, and behavior. When stable isotopes serve as a proxy for diet, correlations between stable isotope signatures, joint dimensions, and diaphyseal cross-sectional properties may reflect several scenarios. Individuals with different diets may consume a different amount of calories or have a heterogeneous risk of malnutrition. In this case, differences in joint dimensions and bone cross-sectional properties will reflect variation due to body mass. In addition, correlations between diaphyseal cross-sectional properties, shape, and stable isotope signatures can arise from different subsistence behaviors necessitating different levels of habitual loading, terrestrial mobility, and the use of different technologies.

1.4 Previous Studies on Dietary Reconstruction in Late Roman- Early Byzantine and Islamic Spain (300-1235 AD)

Recent years have seen an increase in the number of isotope studies of archaeological populations in Spain for both dietary reconstruction and provenance. It is in fact, Ibiza that yielded one of the first Spanish studies in isotope analysis to reconstruct diet (Márquez-Grant et al., 2003), with previous studies particularly focusing on trace element analysis (e.g. Subirà and Malgosa, 1992; García and Subirà, 2001). Prior studies of Ibizan diet based on δ^{13}C and δ^{15}N stable isotopes of bone collagen indicate that, from the Roman to the Islamic period, Ibizan diet predominantly consisted of C_3 cereal crops (*e.g.* wheat, barley, and, in the Islamic period, rice) (Fuller et al., 2010; Nehlich et al., 2012; Alaica et al., 2018). Supporting this interpretation, historical sources, archaeological remains (e.g. ploughs, mills, terraced lands) and archaeobotany identify cereal crops such as wheat and barley as main dietary staples from the Late Roman to the Islamic period (Watson, 1983; Garnsey, 1999, García-Sánchez, 2002; Adamson, 2004; Alonso Martínez, 2005; Salas-Salvadó et al., 2006; Dalby and Granger, 2012; Peña-Chocarro et al., 2019). Oil, nuts, fruit, pulses and legumes supplemented the predominantly cereal-based diet. Both isotopic data and historic accounts further indicate that upper class individuals consumed more meat than lower class individuals (Jiménez-Brobeil et al., 2016; Alexander et al., 2019). The type and quantity of meat consumed also likely varied diachronically. The importance of pork to Roman diet is well known, whereas mainland Medieval Iberian Islamic sites show a greater proportion of sheep and goat remains (King, 2001; Grau-Sologestoa, 2015, 2017). In all time periods, cattle may have predominantly been used for traction rather than food (Grau-Sologestoa, 2015). Cultural prohibitions likely also shaped meat consumption. Islamic law prohibited the consumption of pork and shellfish (Adamson, 2004; Constable, 2013). Poultry, milk, and eggs were also common sources of protein in all archaeological periods.

Although C_3 cereals were dietary mainstays from the Roman to Islamic periods, the potential importance of C_4 crops should not be overlooked. Although considered less desirable than wheat, millet was consumed, particularly by the poor and during times of scarcity in the Roman period (Killgrove and Tykot, 2013; Murphy, 2016). Islamic migration is associated with greater consumption of C_4 crops such as millet, sorghum, and sugarcane (Butzer et al., 1985; Adamson, 2004; Glick, 2005; Peña-Chocarro et al., 2019). Isotopic studies confirm greater consumption of C_4 crops in Islamic Ibizan populations (Fuller et al., 2010; Nehlich et al., 2012; Pickard et al., 2017; Alaica et al., 2018; Dury et al., 2018; Peña-Chocarro et al., 2019). However, the greater isotopic diversity of Islamic individuals may also reflect migration, because isotopic signatures of certain individuals may reflect migration from locations where cultivation of C_4 crops was more extensive (Fuller et al., 2010; Pickard et al., 2017; Dury et al., 2018; Alexander et al., 2019). Thus, it remains unclear whether higher $\delta^{13}C$ values of Islamic populations reflect increased cultivation of C_4 crops, an increase in the number of migrants, or both. Differences in rural and urban diet have not been systematically studied, but it has been previously noted that rural Islamic groups have lower $\delta^{15}N$ signatures than urban groups, a pattern suggesting lower consumption of terrestrial or marine protein (Pickard et al., 2017; Dury et al., 2018).

Recently, a new study has raised the possibility that the contribution of C_4 crops to the Ibizan/ Spanish diet has been underestimated. Dury et al. (2018) examined isotopic signatures of enamel apatite as well as collagen from a single Islamic period urban cemetery. Apatite's chemical composition reflects the combined isotopic values of carbohydrates, protein, and lipids (Jim et al., 2004; Katzenberg, 2008; Dury et al., 2018). While collagen samples indicated a primarily C_3 diet, the apatite $\delta^{13}C$ was consistent with C_4 crops comprising up to 25-40% of the diet. Thus, C_4 crops such as millets or sorghum may have been more important dietary supplements for Ibizan populations than previously appreciated, but their low protein content masks their contribution in collagen analysis (Dury et al., 2018). While these findings are intriguing, their significance remains ambiguous. Apatite isotopes have not been analyzed in other Ibizan samples and sample size (n=6) was small. The analysis may have predominantly sampled migrants. Furthermore, estimates of carbohydrate intake from conventional (i.e. non-Bayesian) mixing models are generally speculative. Therefore, the relative importance of C_4 and C_3 resources in Ibiza diets remains unclear.

Given the terrestrial isotope signatures of Ibiza populations, seafood appears to have been a minor component of Ibizan diet (Fuller et al., 2010; Pickard et al., 2017; Alaica et al., 2018; Dury et al., 2018). Still, given the proximity of the ocean, individuals likely consumed some fish, which may have influenced habitual loading patterns. Consistent with this fishing implements and some icthyofauna have been recovered from archaeological sites, and auditory exostoses, indicators of habitual swimming, have been documented in skeletal remains (Ramon 1995; Márquez-Grant, 2006). Regular use of watercraft or fishing gear (e.g. nets and lines) has been associated with increased upper limb loading, though watercraft use may have a greater effect on upper limb cross-sectional properties than shoreline fishing (Stock and Pfeiffer, 2001; Weiss, 2003; Osipov et al., 2016). Many Roman sources depict fish as the food of the destitute, suggesting cultural mores against habitual consumption (Purcell, 1994; Donahue, 2015). On the other hand, upper class individuals did not embrace this stigma, and garum a fish sauce was ubiquitously consumed (Purcell, 1994; Prowse et al., 2004). Likewise, Christian individuals may have consumed more fish than Islamic people due to fasting rules prohibiting meat, but whether such dietary practices would affect bulk collagen analysis remains unclear (Adamson, 2004; Constable, 2013; Pickard et al., 2017).

Although this study focuses on Ibiza, comparing dietary trends to those seen in mainland archaeological populations places Ibizan dietary patterning into a larger context. The most noticeable similarity between the mainland and Ibiza is the association between Islamic rule and greater reliance on C_4 foods (Salazar-García et al., 2014; Alexander et al., 2015, 2019). As hypothesized for Ibizan populations, C_4 signatures may reflect the cultivation of new crops, a greater proportion of migrants from areas in which these crops were more extensively cultivated, or some combination of these factors. In addition, greater reliance on C_4 crops may reflect lower socioeconomic status, as higher status medieval individuals tend to have C_3 based diets that also contain a higher proportion of animal products (Alexander et al., 2015; Pickard et al., 2017). While consumption of C_4 crops likely increased during the Islamic period, their importance prior to this should not be understated. Notably, in the Northwest Iberian peninsula, the decline of Roman political control corresponds to a growing dependence on C_4 cereals such as millet, and similar patterning is seen in Italian sites (Iacumin et al., 2014; López-Costas and Müldner, 2016). It remains unclear if altered agricultural practices reflect worsening economic conditions, changing climate, or influx of new populations with different dietary habits are responsible for increased dependence on C_4 crops in Late/ post-Roman contexts. Similarly, analysis of Late Roman/ Early Byzantine populations from Ibiza tentatively suggests a small but significant consumption of C_4 cereals (Alaica et al., 2018). Thus, taken together, studies of other Iberian and Mediterranean populations suggest that Ibizan diachronic trends in diet generally follow those seen on mainland Spain. Diets were predominantly based on C_3 crops. Individuals also consumed C_4 crops, and isotopic signatures indicating greater consumption of C_4 crops may reflect migration or differences in social status. Overall, variation in the behavior and physiological stress levels of Ibizan populations from the Roman to Islamic period has not been well-explored. The extent to which dietary variation related to differences in behavior, body size, and physiological stress levels in Ibiza population from the Roman to Islamic Period has not been addressed in these previous studies. Exploring this topic would improve understanding of past populations of the Balearic Islands and the Iberian peninsula.

1.5 Research Goals

The analysis explores the following questions:

1. Did body size and bone cross-sectional properties vary in urban and rural populations dating to the LREB and Islamic periods (300-1235 AD)? If significant differences are detected, what does this reveal about chronological and geographic variation in physiological stress levels and behavior?

2. How does variation in body mass, diaphyseal length, and bone cross-sectional properties correlate with variation in stable isotope signatures? If correlations exist, what do they reveal about the effect of diet on levels of physiological stress and behavior in the specific historical and environmental context?

2. Materials and Methods

2.1 Sample Description

A total of 222 individuals from eight cemetery sites provided data for analysis of body, size, bone length, and cross-sectional properties. Stable isotope data was available for 115 individuals. Sample sizes by cemetery are reported in Table 1. For analysis of correlations between stable isotope values and aforementioned bone properties, sample size ranged from 86 to 20 individuals, depending on the measure employed. All individuals were fully mature adults, as determined by the lack of open epiphyses and mature dentition. Due to poor preservation of the sample, many individuals lack measurements for one or more variables, and it was not possible to reliably estimate sex for a majority of the individuals under study. Previously sex estimates were made using discriminant function analysis of long bone length based on modern Spanish standards or examination of the sciatic notch alone (Màrquez-Grant, 2006; Kyriakou et al., 2012). Pubic symphysis or cranial morphology was rarely assessable. These sex estimates were therefore considered unreliable, especially since chronological change in sex differences is of interest. Nevertheless, data from as many excavated sites as possible has been obtained in order to undertake this study and the number of individuals is indeed a reflection of these practical limitations regarding poor preservation, bone condition, and completeness.

Here we present a brief description of cemetery sites. For more in-depth description, please refer to cited sources. Late Roman Early Byzantine individuals come from four urban or semi-urban cemeteries all located in or around Ibiza town (Via Púnica 33, Joan Planells, Carrer Arragó 33, S'Hort des Llimoners). Twenty-eight individuals come from the cemetery of Via Púnica, dating to 300-400 AD (Llinas and Casanova, 2009). Most burials were in cist graves, and grave goods were typical for pre-Christian Roman funerary traditions. Twenty-one individuals come from the cemetery located in the street of Joan Planells (300-700 AD). This site was also located just outside the old city wall, and the majority of these individuals were interred in cist burials with few grave goods (Esquembre et al., 2005; Girdwood et al., 2011). S'Hort des Llimoners is also located just outside the city wall and the cemetery was used between 300-700 AD, though the bulk of burials date from between 300-500 AD (Ramon et al, 2005). Graves surround two funerary structures on either side of a main Roman road. This analysis includes 11 individuals from this cemetery (Marquez-Grant, 2006). Individuals buried at Carrer Aragó 33 were interred between 300-600 AD, but most burials date to the 500-600 AD (Torres, 1995; Marquez-Grant, 2006). In the laboratory the remains were presented as a commingled assemblage From a total minimum of 28 individuals from this assemblage , a total of 21 femora, 24 tibiae, and 9 left humeri as well as 3 right humeri recovered paired with left humeri were employed.

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The Islamic period sample consists of individuals from four urban cemeteries in Ibiza town (Es Soto, Carrer Major, Avenida de España, and Puig des Molins) and one rural cemetery (Can Fonoll) all dating according to their funerary rite to between 902 and1235 AD. Burials are typical of the Islamic style: individuals lying on their right side with heads to the SW and face facing SE towards Mecca. Except for Carrer Major with one adult individual, all the other cemeteries are located beyond the city walls. Although traditionally considered contemporaneous with Islamic rule, it is possible that some burials from Es Soto are of Islamic slaves from the subsequent period of Christian control (1235-1500 AD) (Ferrer Arbázurza, 2015), though radiocarbon dating has not been carried out to confirm this possibility.

Eight individuals are from the site of Es Soto, which was uncovered during two separate rescue excavations (Màrquez-Grant, 1999). One individual is from Carrer Major, the only Islamic cemetery known within the city walls of Ibiza town (Martín Parrilla and Graziani Echávarri, 2008). Nineteen individuals are from Avenida de España, which dates to 902-1235 AD (Gurrea and Ramon n.d.). The site of Puig des Molins, located outside the city walls, was used as a cemetery from the Punic to the Islamic periods (Bellard, 1989). Islamic burials were all interred in earth cut graves. Finally, the Islamic site of Can Fonoll is the only rural site in the analysis. Ninety-six individuals were uncovered during excavation several kilometers from Ibiza town and 83 individuals are included in the analysis (Castro, 2009; Kyriakou et al., 2012; Pickard et al., 2017).

2.2 Body Size and Bone Cross-sectional properties

Where complete diaphyses were available, the maximum length of the femur and humerus, and tibia were measured using an osteometric board. Femoral head diameter, as well as maximum and minimum diameters of bone diaphyses, were measured with sliding calipers. Circumferences were taken with measuring tape. Diaphyseal diameters and circumferences were taken at three locations: humerus midshaft, femur midshaft, and tibia nutrient foramen. In most individuals, diaphyseal length could not be measured due to poor preservation. On fragmented remains, midshaft locations were estimated visually. To reduce measurement error, midshaft measures were taken three times and averaged. The bones that were able to be measured did not present any evidence of infection such as periostitis or any joint disease such as osteoarthritis, which may have affected the measurements.

Femoral head diameter serves as a proxy for body mass, as it is the best preserved joint dimension, and it is also the most commonly used measure for body mass estimation (McHenry, 1992; Grine et al., 1995; Ruff et al., 2012). In this study bone cross-sectional properties provide a proxy for bone strength. Following Stock and Shaw (2007), cross-sectional properties were calculated from external dimensions using diaphyseal products (maximum*minimum diameter) and circumference measurements at set locations of the midshaft humerus, femur midshaft, and tibia nutrient foramen. These locations are commonly used in biomechanical analysis, because they provide good proxies for upper and lower limb loading levels (Ruff, 2008). As it remains unclear whether the femur or tibia provide the best proxy for loading levels, we analyze both elements to quantify lower limb cross-sectional properties (Ruff et al., 2006b; Stock, 2006; Nadell and Shaw, 2016). Diaphyseal shape was calculated as the ratio of maximum to minimum diaphyseal diameters. Maximum and minimum diameters were used instead of anteroposterior and mediolateral diameters, because this avoids the error introduced by misalignment of anatomical axes. Also, especially in the upper limb, the axis of maximum loading may deviate significantly from the anteroposterior or mediolateral axis. Femur and tibia measures were averaged, and if one side was missing, the value of the single available side was used. Left and right humeral lengths were averaged to increase the sample size, because asymmetric loading does not markedly affect bone length (Trinkaus et al., 1994; Auerbach and Ruff, 2006). However, given the potential for asymmetric loading due to handedness, left and right humeral diaphyseal products and circumference were also analyzed separately (Auerbach and Ruff, 2006; Sládek et al., 2016). If only one humerus was preserved, this value was used for the average.

Due to a lack of diaphyseal lengths and articular surfaces it was not possible to control for differences in body size for most individuals. Measures of bone length and joint dimensions are commonly used to standardize cross-sectional properties measures for body size (Ruff, 2000). However, few individuals have fully preserved long bones or femoral head dimensions. Also poor preservation of cranial and pelvic remains prevented sex estimation in a majority of individuals. Therefore differences between samples in body size, stature, and cross-sectional properties could reflect unequal sex distributions. Following May and Ruff's (2016) previous analysis of poorly preserved samples, size-unstandardized cross-sectional properties measures were used to compare samples with no division by sex. Comparisons of the smaller number of femoral head and bone length measurements allowed a critical evaluation of differences in body size on bone cross-sectional properties. The potential effects of body size and a lack of sex estimates are explicitly addressed in the discussion. We also report the coefficient of variation to evaluate potential differences in sexual dimorphism between samples (Villmoare et al, 2019). Also it should be noted that given their relationship to body size, analysis of cross-sectional properties can directly provide new insight into variation in body size (Pomeroy et al., 2018).

Lastly, diaphyseal products and circumferences do not quantify diaphyseal strength and shape as accurately as cross-sectional geometry calculated from combined periosteal and endosteal contours (Stock and Shaw, 2007; Sparacello and Pearson, 2010; Davies et al., 2012). However, obtaining this data requires CT scans or a combination of periosteal molds and biplanar radiographs, which were unavailable when measurements were collected. Stock and Shaw (2007) found strong correlations between measures of bone strength and shape derived from true periosteal contours and estimates of endosteal contours and bone diameters/circumferences. Average standard estimates of the error for measures of bending rigidity derived from diaphyseal products or circumferences ranged between 20-23 percent, though individual errors may be substantially higher or lower. Overall, prior investigations have concluded that diaphyseal products and circumferences provide a reasonable approximation of group differences in cross-sectional properties when sample sizes are sufficiently large. Therefore, the use of external dimensions should provide an accurate picture of biomechanical differences between the populations examined.

2.3 Stable Isotope Analysis

The methodology for extracting bone collagen and stable isotope analysis has been previously described in Pickard et al. (2017), Alaica et al. (2018), and Fuller et al (2010), and these protocols were followed. Briefly, bone samples were cleaned, demineralized, and gelatinized before mass-spectrometry. Isolation of well-preserved collagen was indicated by C:N ratios between 2.9 and 3.6. Five individuals with C:N ratios outside this range were excluded from analysis.

2.4 Sample Comparisons and Statistical Analysis

The Urban LREB sample was compared to the Islamic Urban and Rural samples. A Shapiro-Wilks test was carried out to test for normal distribution. If variables were normally distributed, bone length, body mass, and diaphyseal cross-sectional properties the three samples were then compared using a one-way ANOVA with Tukey HSD post-hoc comparisons. For non-normally distributed variables, non-parametric Kruskal-Wallis tests with the Dunn post-hoc comparison were carried out. Data was analyzed with the R statistical package. Outliers were defined as values above or below 3 standard deviations from the mean, and removed prior to testing. Correlations between osteological measures and $\delta^{13}C$ and $\delta^{15}N$ were evaluated by regressing relevant bone dimension on isotope ratio values using Ordinary Least Squares regression (OLS). Correlations were assessed both for the combined sample and separately for LREB and Islamic samples. Due to the small number of Urban Islamic individuals with both osteometric and stable isotope data, the Islamic sample was analyzed both with urban and rural components combined and separated.

3. Results

3.1 Body Size, Diaphyseal Length, and Diaphyseal Cross-sectional properties

Descriptive statistics for all variables by group are given in Table 2. Boxplots with sample sizes are presented in Figure 1 for femur head maximum breadth and bone lengths. Due to the small number of sufficiently preserved humeri, only the mean length (pooled left and right) is presented. For all variables, coefficients of variation are fairly similar for bone lengths, femur head diameter, and shape ratios (Table 2). The Urban Islamic group exhibits a slightly higher coefficient than other groups only for lower limb diaphyseal products and circumferences. Statistical comparisons of femoral head and bone lengths, presented in Table 3, show no significant differences in femoral head breadth or limb length between groups, though the Rural Islamic group produces the lowest range for femoral head breadth. Also, the

Rural Islamic group has significantly shorter humeri than Urban Islamic and Urban LREB individuals (Tables 2 and 3).

Table 2

Figure 1

Table 3

Boxplots for diaphyseal products and circumferences by cemetery are given in Figures 2 and 3. The lower cross-sectional properties of the Rural Islamic population are clearly apparent. Statistical comparisons in Table 3 demonstrate that Rural Islamic individuals have significantly lower upper and lower limb cross-sectional properties than Urban LREB individuals, but comparisons of Rural to Urban Islamic individuals are only significant for the lower limb. Urban LREB and the Urban Islamic group do not show significant differences in diaphyseal circumference or products. Boxplots for shape ratios are given in Figure 4 and descriptive statistics in Table 2. Statistical comparisons in Table 3 indicate that Urban Islamic individuals have significantly higher humerus midshaft and lower tibia nutrient foramen shape ratios than the Urban LREB group. In other words, the Urban Islamic group has less circular humeri and more circular tibiae than the Urban LREB group.

Figure 2

Figure 3

Figure 4

3.2 Correlations between Stable Isotope Signatures and Osteometric Variables

R-squared values are provided in Table 4 for OLS regressions of femur head breadth, bone length, and diaphyseal products, circumferences, and shape on $\delta^{13}C$ and $\delta^{15}N$. Regressions were carried out for the combined sample and separately for the Urban LREB and Rural Islamic groups. Prior studies did not sample the majority of Urban Islamic individuals for which osteometrics are available for stable isotopes analyses. For this reason, sample size for this group is four individuals for the femoral head and one individual for other variables. To address this issue, correlations are reported only for the combined, Urban LREB, and Rural Islamic samples. Pooling the Urban Islamic individuals with the LREB Urban group or the Rural Islamic group did not change the results. Visual analysis assesses if Urban Islamic individuals depart markedly from significant correlations seen in other groups.

Table 4

A significant positive correlation exists between $\delta^{13}C$ and femur head diameter for the combined sample and for the Urban LREB group, as $\delta^{13}C$ increases femoral head diameter also increases (Table 4). A scatterplot of femoral head breadth plotted against $\delta^{13}C$, given in **Figure 5**, shows that a lack of correlation in the Islamic Rural group results from one individual with a high $\delta^{13}C$ value but low femoral head diameter. Prior research has concluded this individual is non-local to the island and almost certainly a migrant from Africa (Pickard et al., 2017). If this individual is excluded, the regression becomes significant. While the Urban Islamic correlation does not reach statistical significance, the five individuals do exhibit a positive trend, and the regression remains significant in the combined Urban and Rural Islamic sample. This group also contains an outlier with an even more positive isotopic value than the Rural Islamic outlier. In the combined sample, $\delta^{13}C$ also correlates significantly with femur and humerus length (Table 4). Individuals with higher $\delta^{13}C$ have longer femora and humeri. When regressions are carried out by group, the femur regression remains significant in both the Urban LREB and Rural Islamic sample. The plot for femur length is given in **Figure 6** with significant regression lines shown.

Figure 5
Figure 6

Regressions of combined sample diaphyseal products and circumferences on $\delta^{13}C$ are significant for all locations, though correlation coefficients are very low ($R^2<.1$) (Table 4). A scatterplot of femoral circumference regressed on $\delta^{13}C$ is provided as an example in Figure 7. Individuals with higher carbon isotope values have more robust bones. Further analysis by group only found a significant positive relationship between $\delta^{13}C$ and right humerus diaphyseal product and circumference in the Urban LREB group. Regressions of shape ratios on $\delta^{13}C$ are not significant.

Figure 7

Nitrogen isotope ratios show no significant correlations with skeletal measures in the combined sample. However, for the Urban LREB period left humerus maximum/minimum humerus diameters shows a significant positive correlation with $\delta^{15}N$ ($R^2= 0.17$) (Table 4). As seen in the bivariate plot of left humerus shape on $\delta^{15}N$ in Figure 8, individuals with higher $\delta^{15}N$ have less circular humeri.

Figure 8

4. Discussion

4.1 Summary of Results

The goal of this study was to determine if there were differences in physiological stress levels and behavior between urban and rural Ibiza populations dating from the LREB-Islamic period. We also investigated if differences in behavior and physiological stress correlate with differences in diet. The Rural Islamic sample has significantly shorter humeral diaphyses than the Urban LREB and Urban Islamic populations (Figure 1; Table 3). Comparisons further highlight the low cross-sectional properties of Rural Islamic individuals (Figures 2 and 3; Table 3). The Urban Islamic group has less circular humeri and more circular tibiae than the Urban LREB group (Table 3). Femoral head breadth and length correlate positively with $\delta^{13}C$ values in the entire sample, and separately in the Urban LREB and combined Islamic/ Rural Islamic groups (Table 4; Figure 5). Diaphyseal cross-sectional properties measures also show a positive correlation with $\delta^{13}C$ in the combined sample, though the correlations appear weaker than for femoral head diameter (Figure 7; Table 4). Left humerus shape exhibits a positive correlation with $\delta^{15}N$ in the LREB Urban group (Figure 8).

4.2 Limitations

This study has several limitations. First, sex could not be reliably estimated. Due to sexual dimorphism in body size and musculature, males would have longer limbs, greater body mass, and more robust diaphyses than females. Additionally, testosterone increases the sensitivity of the periosteum to loading, further contributing to greater male cross-sectional properties (Frisancho et al., 1970; Orwoll, 2003; Schoenau, 2006; Högler et al., 2008; Gabel et al., 2017). Consequently, males may appear more robust even if habitual loading levels relative to body size did not differ between the sexes (Stock and Macintosh, 2016). Culturally mediated variation in behavior, diet, and social status are also important sources of sexual differences in body size and cross-sectional properties. Thus, one cannot exclude the possibility that some of the differences detected between populations may reflect uneven sex distributions combined with varying levels of dimorphism. Coefficients of variation for bone length and femur head diameter are equivalent across groups compared, suggesting that populations are equally heterogeneous in terms of body size (Table 2). The Urban Islamic group exhibits a higher coefficient than other groups for diaphyseal products and circumferences. A potential explanation for this might be higher levels of sexual dimorphism in levels of loading. On the other hand, variability in load levels between Urban and Rural Islamic groups may also reflect a greater diversity of behaviors in an urban population compared to a rural population. However, the Urban Islamic coefficient is higher than that of the Urban LREB sample, and the reasons for this are unclear.

The reduced accuracy of estimates of cross-sectional properties calculated from external dimensions compared to those based on "true" periosteal and endosteal contours has been noted in the methods section. However, the unavailability of radiographic imaging limited analysis to external dimensions. Still, Stock and Shaw (2007) note that diaphyseal products and circumferences show strong correlations with cross-sectional properties calculated using direct imaging of cross-sections and mean values are mechanically meaningful. Thus this is the best method currently available for biomechanical analysis, and it should reliably capture differences between groups. Also, diaphyseal cross-sectional properties could not be standardized for differences in body mass and length, the two determinants of load related to body size, complicating behavioral reconstruction (Ruff, 2000). Some prior studies have size-standardized diaphyseal products by femoral head diameter alone or a body mass estimate derived from this measure (Wescott, 2006). However, this would dramatically decrease sample size. Furthermore, Stock and Shaw (2007) found that diaphyseal products standardized by femoral head size showed weak correlations with size-standardized measures of bending/ torsional rigidity derived using cross-sectional geometry. Correlations improved if products of bone length and body mass were used, which is not practical given the poor preservation of Ibiza skeletal material. The potential effect of body size and diaphyseal length on comparisons of bone cross-sectional properties is discussed in greater detail below. Lastly, it should be noted that cemeteries cover centuries of occupation and dating has not been undertaken on each individual. Therefore, the results essentially represent "averages" for the periods compared, and they are blind to changes within archaeological periods.

4.3 Chronological Variation in Body Size and Habitual Behavior

Rural Islamic mean values for humerus length are significantly lower than in the Urban LREB and Islamic samples (Table 3). Rural Islamic individuals also have significantly smaller lower limb diaphyseal products and circumferences than the Urban LREB and Urban Islamic groups (Tables 2 and 3). Upper limb cross-sectional properties exhibit more complex patterning. The Urban LREB group differs significantly from the Rural Islamic group but the Urban Islamic group does not. Reduced humerus length in the Rural Islamic sample may contribute to this patterning, because reduction in moment arm decreases mechanical strain. However, this would not account for a lack of differentiation from the Urban Islamic group.

The lower cross-sectional properties of the Rural Islamic group prove unexpected. Given the intense habitual loading involved in agricultural labor, one would expect greater cross-sectional properties than in urban groups. If these findings do reflect activity differences, lower habitual workloads among the Rural Islamic group could potentially reflect technological innovations in farming and manufacture. Following

Islamic settlement, irrigation improved and watermills were constructed for grinding grain, potentially reducing the strenuousness of agricultural labor (Butzer et al., 1985; Kirchner, 2009). The relative robusticity of the urban samples could reflect habitual engagement in more strenuous labor than the Rural Islamic group. No prior study has directly compared rural and urban Islamic populations. However, a prior study of Punic remains found greater evidence of osteoarthritis in rural compared to urban Punic groups, which suggests greater habitual loading in the former, contradicting lower workloads in rural groups (Márquez-Grant, 2006).

One also cannot exclude genetic change due to increased migration as a contributing factor to the distinctive skeletal phenotype of rural Islamic individuals. Studies of settlement patterns suggest abandonment of rural sites outside of urban nuclei in the Balearic Islands at the beginning of the LREB (Florit and Ontiveros, 2011). This may have led to the repopulation of rural spaces by a phenotypically distinct group in the Islamic period, though repopulation appears to have already begun in the Early Byzantine period (Ramon 1995; González and Pacheco, 2002). Still significant migration took place during the Islamic period, as evidenced by the distinct craniometrics and non-metric trait frequencies of Islamic Ibiza populations, as well as the frequency of non-local isotopic signatures in Islamic populations and land rents with names of Arabic-Berber derivation, which suggest a North African and/or sub-Saharan origin (Kirchner, 2009; Fuller et al., 2010; Girdwood, 2012; Nehlich et al., 2012; Kranioti et al., 2015; Pickard et al., 2017). Thus the reduced cross-sectional properties and bone length of the rural sample may reflect the influx of a phenotypically distinct population. Diachronic stability in skeletal phenotype among urban groups may indicate that either the genetic contribution of migrants was subsumed within a larger population or that urban and rural migrants had different origins. However, it remains unclear if genetically encoded differences in diaphyseal robusticity and bone length can be so large as to overshadow the effect of mechanical loading, diet, and disease load on bone dimensions (Frisancho et al., 1980; Adams and Ackert-Bicknell, 2015).

As it seems improbable that rural individuals performed markedly less strenuous labor than urban groups or that genetic differences could completely account for differences in skeletal phenotype, reduced body size offers the most convincing explanation for the gracility of the Rural Islamic sample. Studies of relationships between body size and skeletal dimensions have noted stronger correlations between cross-sectional geometry and body size than joint dimensions or bone length (Lieberman et al., 2001, 2004; Ruff, 2007; Cowgill, 2010, 2017). Also, while femoral head size does not differ significantly between groups, the Rural Islamic sample produces the lowest range, and humeral length is significantly lower (Figure 1). Therefore, it may be the case that lower Rural Islamic robusticity reflects reduced body size due to differences in diet quality and disease load. Prior studies provide contradictory evidence for greater physiological stress in the Rural Islamic population. Kyriakou et al. (2012) found that Rural Islamic individuals exhibit a similar prevalence of skeletal lesions, cribra orbitalia and linear enamel hypoplasia, indicative of malnutrition and illness, as other Ibizan populations. On the other hand, Kyirakou et al. (2012) also found that Rural Islamic individuals had smaller stature and diaphyseal length than LREB Ibizan populations or contemporaneous mainland Spanish Islamic and Christian populations, though small sample size makes these conclusions tentative. Nevertheless, our findings are consistent with reduced body size in the Rural Islamic sample, emphasizing the uniqueness of this population compared to other Ibizan and mainland populations. A recent study has shown a greater prevalence of caries in rural than urban Islamic populations, supporting dietary differences between the rural and urban groups (Márquez-Grant and Busom, n.d.). Also, $\delta^{15}N$ is lower in the Rural Islamic group than Urban Islamic samples, which may reflect reduced consumption of meat (Dury et al., 2018). Therefore differences in body size may reflect reduced diet quality in the Rural Islamic group. It is possible, for instance, that populations of the port city had greater access to or the financial means to purchase imported food.

Homogeneity in femur midshaft shape suggests similar levels of mobility across groups (Figure 4; Table 3). Contradicting this, the Urban Islamic group has a more circular tibia nutrient foramen section compared to the LREB Urban group. In the upper limb, significant differences in humeral shape between Urban LREB and Islamic groups suggest a difference in the habitual range of motion (Figure 4; Table 3). The Islamic Rural group exhibits an intermediate range of values, and does not differ significantly from either urban group. The contradictory lower limb results are difficult to reconcile, but prior studies have noted that femur midshaft shape shows a closer linkage to inferred habitual mobility than the tibia (Stock, 2006). Therefore, the weight of the evidence does not clearly support differences in habitual mobility. Furthermore, it has been noted that lower limb shape can also vary due to differences in body shape (Ruff et al., 2006b; Wescott, 2014). Thus, given the previously discussed importance of migration, genetic differences in the limb shape of Ibiza populations cannot be excluded. As well, habitual behaviors other than mobility (*e.g.* plowing, horseback riding, spear throwing) may differentially influence femur and tibia, as well as humerus shape (Wescott, 2014; Cameron et al., 2018). For these reasons, differences between the two urban samples in tibia and humerus shape may represent a chronological change in the types of habitual activity practiced. Given the wide range of trades practiced within an urban environment, identifying the specific activity responsible for shape differences is not possible. Still, Islamic expansion into the Balearic Islands brought technological change (Florit and Ontiveros, 2011; Heiss et al., 2014). Therefore, it is not unreasonable to suggest that the types of activities practiced in economic centers such as the port city of Ibiza town may have changed diachronically.

4.4 The Effect of Diet on Body Size and Cross-sectional properties

Analysis of correlations between stable isotope signatures and skeletal dimensions showed that $\delta^{13}C$ correlated positively with femoral head diameter and femoral length in the Urban LREB and Islamic Rural/ combined Islamic Rural and Urban sample (Table 4; Figures 5 and 6). The correlation of $\delta^{13}C$ to humerus length was only significant in the combined sample of all individuals from all time periods. While the relationship does not reach statistical significance, the Urban Islamic sample shows a positive trend between femur head diameter and $\delta^{13}C$. In the combined sample of all individuals, diaphyseal cross-sectional properties correlate positively with $\delta^{13}C$ values, but the correlation is notably weaker than for femoral head breadth (Figure 7).

The consumption of C_4 resources elevates $\delta^{13}C$ relative to a diet based exclusively on C_3 resources. Consequently, the positive correlation between femoral head, femur length, humerus length, and carbon isotope ratios suggests that greater access to C_4 crops or animals consuming those crops was associated with higher body mass and stature (Figure 5). On the basis of past studies, the relationship between C_4 foods and body size proves surprising, because it has been thought that C_4 resources constituted a minor part of local Ibizan diet, especially in the LREB period (Fuller et al., 2010; Pickard et al., 2017; Alaica et al., 2018). However a recent study based on enamel apatite suggests that collagen analysis underestimates the contribution of C_4 resources to the Ibiza diet during the Islamic period (Dury et al., 2018). The same issue may have led to an underestimation of the amount of C_4 resources in LREB diet. Greater access to C_4 crops could have increased body size in two ways. First, it may have improved regular caloric intake. Second, in times of shortfall, locally raised or imported millet and sorghum, which are resistant to drought and have shorter growing seasons than major C_3 crops, may have been fallback foods, ensuring the consumption of sufficient calories and nutrients. Similarly, López-Costas and Müldner's (2016) study of post-Roman diet in Northwest Spain suggested that millet may have been particularly important when "a hard winter or other event ruined crops with longer growing seasons" (p. 149). The positive correlation between access to C_4 foods and body size could further indicate differences in food access due to socioeconomic status or social connections. For instance, Islamic settlement of the island appears to have been organized on the basis of clans, which may have had variable access to imported C_4 foods or farmed different crops (Kirchner, 2009; Dury et al., 2018). Familial or class differences in financial resources or subsistence strategies may similarly explain variation in access to C_4 foods during the LREB period. Also, absent better biological data on sex, one cannot exclude the possibility that the positive correlation also reflect greater consumption of C_4 resources by men, because their higher body mass would lead to the appearance of a positive correlation.

Correlations between diaphyseal cross-sectional properties and $\delta^{13}C$ are also significant, but R^2 values are markedly lower than for the femoral head and humerus/ femur length (Table 4; Figure 7). The weakness of the correlations may reflect that both body mass and activity generated loads affect cross-sectional properties. Individuals consuming more C_4 resources have higher body mass, but the additional variation introduced by activity related loading largely swamps this signal. Thus while body size was affected by differences in C_4 resource consumption, habitual loading levels may not have differed markedly between individuals with different diets. However, confirming this will require analyzing the effects of body mass and bone length on the correlation between cross-sectional properties and $\delta^{13}C$ using a larger sample in which body size can be controlled for. Alternatively, bone cross-sectional properties and femoral head/ length may provide information about the relationship between body mass and diet at different points in the life course. Cross-sectional properties tracks changes in body mass throughout life to a greater extent than articular dimensions, which show the closest correspondence to late adolescent body size (Ruff et al., 1991; Lieberman et al., 2004; Ruff, 2007; Pomeroy et al., 2018). Therefore, the stronger correlation of femoral head diameter than cross-sectional properties to $\delta^{13}C$ might reflect that diet had an especially strong impact on body size during growth. Diet can change throughout life, and it has been generally estimated that bone collagen may take 10-30 years to fully turnover (Libby et al., 1964; Hedges et al., 2007). More recently, studies have shown that stable isotope signatures of midshaft cortical bone essentially become fixed in adolescence (Matsubayashi and Tayasu, 2019). While preservation issues complicate age assessment, the majority of individuals analyzed are young or middle-aged adults. In this age-range, cortical bone would predominantly reflect adolescent diet even if one uses the most precocious estimates of bone turnover. Although diet can shift throughout life, prior analyses of Islamic and LREB populations from Ibiza did not show age-differences in stable isotope signatures (Pickard et al., 2017; Alaica et al., 2018). Thus, our results tentatively suggest the intriguing possibility that access to C_4 resources may have been especially important for developmental health. However, it remains unclear if C_4 foods were consumed as fallback foods or regularly. Sporadic consumption of C_4 fallback foods would not likely affect bulk collagen samples. For instance studies combining isotopic analysis of bulk collagen and dentine have shown that bulk collagen does not record sporadic dietary changes whereas dentine, which is laid down serially, does (Montgomery et al., 2013). Thus, it may be most parsimonious to assume that the correlation between body size and carbon isotope signatures reflects lifelong differences in diet rather than the use of fallback foods during growth.

A positive correlation between $\delta^{13}C$, femur head diameter, and bone cross-sectional properties may not entirely reflect variation in local diet. It is also possible that it indicates greater body size among migrants.

Individuals raised outside of Ibiza, in areas more dependent on C_4 resources, may have had higher body mass due to either the positive effect of C_4 resources on diet quality/ health or genetic differences. Exploring this possibility would require further studies that employed sulfur, strontium, and oxygen isotope ratio analysis to explicitly identify migrants in these cemeteries. The Islamic period rural and urban individuals with markedly high $\delta^{13}C$ values and low femoral head values marked in Figure 5 provide another example of potential heterogeneity in diet and body size due to migration. Including these individuals in the analysis makes the linear correlation between femoral head and $\delta^{13}C$ non-significant. Pickard et al. (2017) hypothesized that the rural individual was a migrant from Africa, who spent a significant portion of their life in an area where individuals depended to a greater extent on the C_4 food web. As a result, a different set of "dietary rules" potentially applied, with greater access to C_4 resources not correlating with increased dietary quality or body size. The same may be true of the urban individual. Prior analysis of medieval diet on mainland Spain has also linked differences in the consumption of C_4 resources to social status or migration (Alexander et al., 2015, 2019). However, it remains unknown if $\delta^{13}C$ also correlates with phenotypic variation in mainland groups.

Lastly, femoral head size and bone cross-sectional properties did not correlate significantly with nitrogen isotope ratios (Table 4). This suggests that higher consumption of marine or terrestrial fauna did not correlate with higher body size or habitual loading. Given the overwhelmingly cereal based terrestrial diet indicated by isotopic data and historical sources, this finding is somewhat unsurprising, though *a priori* one might have expected some socioeconomic patterning (Purcell, 1994; Donahue, 2015; Pickard et al., 2017; Alaica et al., 2018; Dury et al., 2018). However, greater meat consumption may be linked to habitual use of the upper limb for different types of activities. Left humerus shape shows a significant positive correlation to $\delta^{15}N$ in Roman/LREB individuals, indicating that the difference between maximum and minimum diameters increases as $\delta^{15}N$ increases (Table 4; Figure 8). As previously stated, the complex mechanical environment of the upper limb complicates behavioral interpretations. One potential explanation for this positive correlation is differential use of the upper limb by individuals acquiring marine resources, since such foods would especially raise $\delta^{15}N$ values. Fishing implements and some icthyofauna have been recovered from archaeological sites, and auditory exostoses, indicators of habitual swimming, are evident in skeletal remains (Ramon 1995; Márquez-Grant, 2006). Interestingly, Alaica et al.'s (2018) analysis of LREB individuals from Joan Planells found two individuals with relatively high $\delta^{15}N$ values, a pattern consistent with intra-group variation in marine resource consumption. Using fishing gear and piloting watercraft might lead to less circular humeri due to repetitive unidirectional loading (*e.g.* rowing, line hauling, swimming). As boat-use is often associated with bimanual loading due to the use of oars, it is unexpected that correlations would be significant for only the left humerus (Table 5)

(Weiss, 2003). However, fishing and sailing also involve other activities such as gutting, throwing, and hauling lines that may place significantly higher strains on one arm. Also, as Alaica et al. (2018) only found two Joan Planells individuals with outlying high $\delta^{15}N$ values consistent with marine resource consumption, small sample size may explain the lack of significance in right and average values. There are also potential explanations for the correlation between $\delta^{15}N$ and humerus shape other than fishing. For instance, individuals with higher $\delta^{15}N$ may represent higher status individuals with the resources to purchase meat and fish. In this case, the correlation would not directly stem from subsistence behavior but actually reflects a difference in the types of behaviors engaged in by individuals of different socioeconomic status.

5. Conclusion

The current analysis improves understanding of chronological variation in physiological stress, behavior, and diet among urban and rural Ibizan populations from the Late Roman/ Early Byzantine to the Islamic period. Urban populations from the LREB to the Islamic period show equivalence in body size and loading levels, whereas Islamic Rural groups exhibit evidence of reduced body size and habitual loading compared to urban groups. The differentiation of Islamic Rural from urban populations might reflect differences in workload or genetic differences. However, a more convincing explanation is increased physiological stress among rural populations due to poorer diet. Only limb shape differentiates the Urban LREB and Islamic groups, which may reflect a diachronic change in the type of activities but not the strenuousness of workloads. Analysis of the effect of diet on skeletal dimensions identified a relationship between $\delta^{13}C$ and body size. One explanation for this pattern is that greater access to C_4 resources improved diet quality or allowed for supplementation of the diet during periods of nutritional shortfall. Alternatively, non-locals from regions that depended more on the C_4 food web tended to be larger than individuals born on Ibiza due to dietary or genetic differences. Additional work would help clarify the relationship between body size, physiological stress, activity, diet, and place of origin in Ibizan and other Mediterranean populations. Future research can apply the techniques employed here to mainland Spain or around the Mediterranean. It could also use non-invasive imaging to assess changes in trabecular and cortical bone quantity due to diet and behavior. Increased sampling of enamel apatite will add further nuance to the understanding of Mediterranean diet. Also, further sulfur, strontium and oxygen isotope studies need to be carried out to identify non-local individuals, and this will clarify differences in behavior and health between locals and non-locals. Overall, this investigation advances understanding of variability in behavior and physiological stress in Ibiza and Mediterranean populations from 300-1235 AD. More broadly, it demonstrates the utility of combining stable isotope analysis with measures of body size and cross-sectional properties. This approach represents a valuable addition to the toolkit for studying biological and cultural change in past populations.

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Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors have no conflicts of interest.

Ethical Statement and Informed Consent

Analysis and data collection carried out for this study followed standard ethical guidelines for the analysis of archaeological human remains.

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Figure Legends

Figure 1: Boxplots of femur head diameter and bone lengths with overlaid raw data

Figure 2: Boxplots of diaphyseal products with overlaid raw data

Figure 3: Boxplots of diaphyseal circumferences with overlaid raw data

Figure 4: Boxplots of diaphyseal shape ratios with overlaid raw data

Figure 5: Scatterplot of femur head diameter regressed on δ13C with group specific regression lines (Outliers marked with arrows)

Figure 6: Scatterplot of femur length regressed on δ13C with group specific regression lines

Figure 7: Scatterplot of femoral circumference regressed on δ13C. Only whole sample regression line shown, as archaeological period specific regressions non-significant

Figure 8: Scatterplot of left humerus maximum/minimum diameter ratio regressed on δ15N with Late Roman/ Early Byzantine period regression line.

Table 1: Sample Sizes by Cemetery and Time Period

Cemetery Site	Archaeological Period/ Group	Osteometrics (N)	Stable Isotope (N)
Via Punica	LREB Urban	28	26
Joan Planells	LREB Urban	21	21
S'Hort des Llimoners	LREB Urban	10	14
Carrer Aragó 33	LREB Urban	24	0
Es Soto	Islamic Urban	8	8
Carrer Major	Islamic Urban	1	0
Avenida de Espana	Islamic Urban	19	0
Puig des Molins	Islamic Urban	2	0
Can Fonoll	Islamic Rural	81	55

LREB: Roman/ Late Roman-Early Byzantine

Table 2: Descriptive Statistics for Femoral Head Breadth and Diaphyseal Lengths, Products, and Circumferences by Cemetery

	Urban LREB				Urban Islamic				Rural Islamic			
Variable	N	Mean	SD	%CV	N	Mean	SD	%CV	N	Mean	SD	%CV
Femur Head Breadth and Bone Lengths (mm)												
Femur Head Diameter	42	44.53	3.2	7.2	22	44.86	3.91	8.7	25	44.14	3.67	8.3
Average Femur Length	24	428.52	32.5	7.6	13	433.58	31.73	7.3	22	409.7	34.44	8.4
Average Humerus Length	21	308.64	19.62	5.8	8	318.38	23.53	6	14	274.79	33.33	12
Average Tibia Length	13	354.73	31.11	8.7	9	359.39	27.54	7.7	1	340	-	-
Diaphyseal Products (mm²)												
Average Femur	51	747.15	127.16	17	14	729.46	203.31	28	62	585.96	113.79	19
Average Tibia	56	768.2	153.08	20	16	794.72	267.11	34	27	624.11	121.83	20
L Humerus	42	398.69	117.08	26	10	431.76	73.33	29	49	323.55	71.67	23
R Humerus	30	417.8	100.28	24	11	366.36	119.82	33	48	329.87	65.36	20
Average Humerus	48	402.25	100.3	25	13	368.31	110.78	30	65	326.68	63	19
Diaphyseal Circumferences (mm)												
Average Femur	51	87.64	7.64	8.7	21	86.73	11.2	13	62	79	7.18	9
Average Tibia	56	91.33	9.82	11	15	88.37	14.96	17	26	80.96	7.71	10
L Humerus	33	65.12	8.43	13	12	61.73	8.56	14	49	60.08	5.67	9
R Humerus	27	65.22	10.39	16	12	64.25	10.86	17	48	60.43	8.74	14
Average Humerus	40	65.35	9.07	14	16	64.49	0.68	15	65	60.57	6.04	10
Diaphyseal Shape Ratios (Maximum/Minimum Diameter)												
Average Femur	51	1.15	0.08	7	14	1.15	0.1	8	62	1.16	0.07	6
Average Tibia	56	1.48	0.11	7	16	1.38	0.08	6	26	1.45	0.13	9
L Humerus	41	1.24	0.09	7	10	1.34	0.14	10	48	1.28	0.11	9
R Humerus	30	1.25	0.11	9	11	1.34	0.09	7	48	1.3	0.11	9
Average Humerus	47	1.24	0.1	8	13	1.33	0.1	7	64	1.29	0.11	8

LREB: Roman/ Late Roman-Early Byzantine
- Insufficient sample size to calculate this statistic

Table 3: Statistical Comparisons of Femoral Head Diameter, Bone Lengths, Diaphyseal Products, Circumference, and Shape

Variable	ANOVA	Post-Hoc		
		LREB Urban-Rural Islamic	**LREB Urban-Urban Islamic**	**Rural Islamic- Urban Islamic**
Femur Head Breadth and Bone Lengths				
Femur Head Diameter	ns	ns	ns	ns
Average Femur Length	ns	ns	ns	ns
Average Tibia Length	ns	-	ns	-
Average Humerus Length[1]	<0.001**	<0.001**	ns	<0.001**
Diaphyseal Products				
Average Femur	<0.001**	<0.001**	ns	<0.001**
Average Tibia	<0.001**	0.001**	ns	0.006**
L Humerus[1]	<0.001**	<0.001**	ns	<0.001**
R Humerus[1]	<0.001**	<0.001**	ns	<0.001**
Average Humerus[1]	<0.001**	<0.001**	ns	<0.001**
Diaphyseal Circumferences				
Average Femur	<0.001**	<0.001**	ns	<0.001**
Average Tibia	<0.001**	<0.001**	ns	0.07*
L Humerus	0.01**	0.006**	ns	ns
R Humerus[1]	0.09*	0.08*	ns	ns
Average Humerus	0.07**	0.005**	ns	ns
Diaphyseal Shape Ratios (maximum/minimum diameter)				
Average Femur[1]	ns	ns	ns	ns
Average Tibia	0.006**	ns	0.005**	ns
L Humerus	0.03**	ns	0.03**	ns
R Humerus	0.06*	ns	0.07*	ns
Average Humerus	0.004**	0.03**	0.01**	ns

LREB: Roman/ Late Roman-Early Byzantine
[-] Comparison not carried out due to insufficient sample size
[1] Values not normally distributed, compared with non-parametric tests
ns: not significant
*significant at 0.05<p<0.1
**significant at p<0.05

Table 4: Sample Sizes (N) and R^2 values for regressions of femur head diameter, bone lengths, and diaphyseal products, circumferences, and shape ratios on δ13C and δ15N

	N				13C			15N		
Variable	Combined	LREBU	RI	UI	Combined	LREBU	RI	Combined	LREBU	RI
Femur Head Breadth and Bone Lengths										
Femur Head Diameter	44	19	20	5	.34**	0.5**	0.33**[1]	ns	ns	ns
Femur Length	24	10	13	1	.1*	0.37**	.18*	ns	ns	ns
Tibia length	4	3	0	1	ns	ns	-	ns	ns	-
Average Humerus Length	21	9	11	1	.17**	ns	ns	ns	ns	ns
Diaphyseal Products										
Femur Midshaft	81	39	42	0	.1**	ns	ns	ns	ns	ns
Average Tibia	49	29	20	0	.07**	ns	ns	ns	ns	ns
Average Humerus Midshaft	85	37	48	0	.1**	ns	ns	ns	ns	ns
L Humerus Midshaft	68	32	36	0	.06**	ns	ns	ns	ns	ns
R Humerus Midshaft	60	25	35	0	.1**	0.08*	ns	ns	ns	ns
Diaphyseal Circumferences										
Femur Midshaft	85	39	43	3	.09**	ns	ns	ns	ns	ns
Average Tibia	49	29	20	0	.09**	ns	ns	ns	ns	ns
Average Humerus Midshaft	86	37	47	2	.08**	ns	ns	ns	ns	ns
L Humerus Midshaft	68	31	36	1	.05**	ns	ns	ns	ns	ns
R Humerus Midshaft	60	25	35	0	.07**	0.08*	ns	ns	ns	ns
Diaphyseal Shape Ratios (maximum/minimum diameter)										
Femur Midshaft	81	39	42	0	ns	ns	ns	ns	ns	ns
Average Tibia	49	29	20	0	ns	ns	ns	ns	ns	ns
Average Humerus Midshaft	83	36	47	0	ns	ns	ns	ns	ns	ns
L Humerus Midshaft	66	31	35	0	ns	ns	ns	ns	0.17*	ns
R Humerus Midshaft	60	25	35	0	ns	ns	ns	ns	ns	ns

LREBU: Late Roman-Early Byzantine Urban, RI: Rural Islamic; UI: Urban Islamic
ns: regression not significant at $p<0.1$
- Comparison not carried out due to insufficient sample size
*regression significant at $0.05<p<0.1$
**regression significant at $p<0.05$
[1]significant at $p<0.05$ if outlier removed

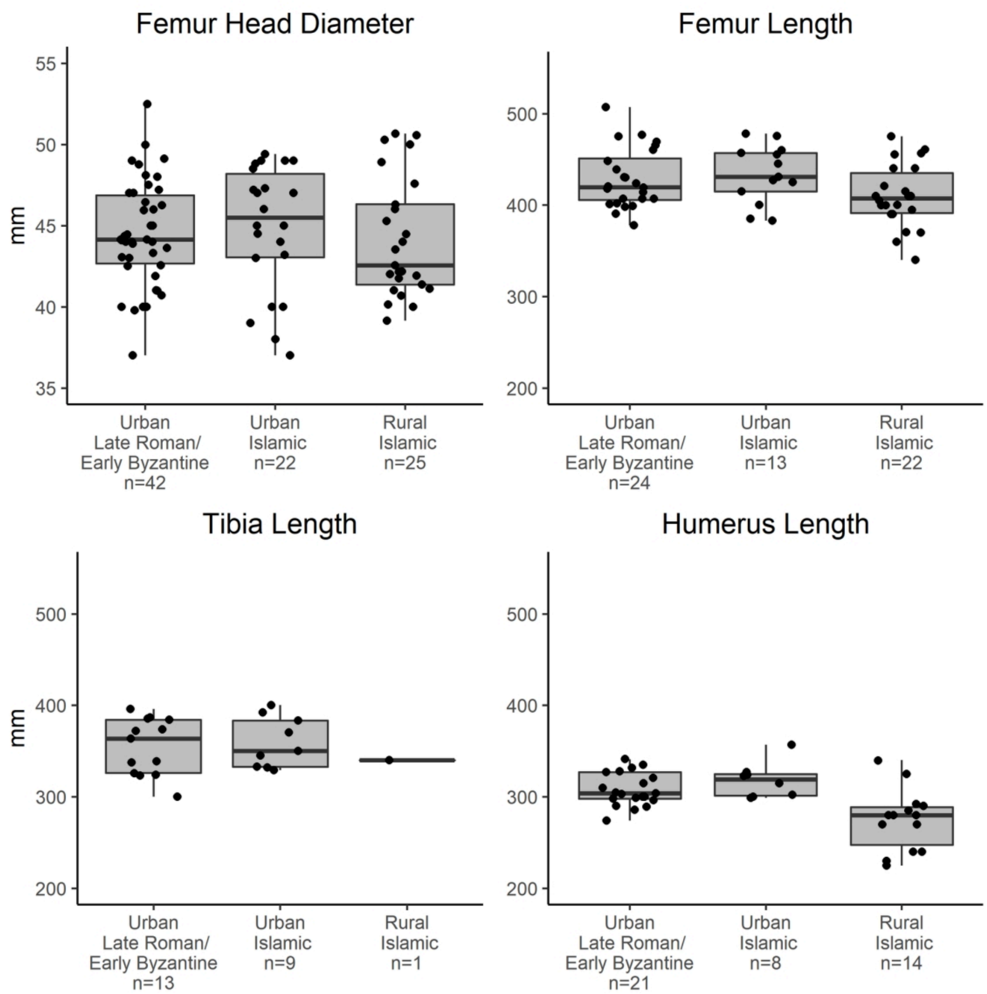

Figure 1: Boxplots of femur head diameter and bone lengths with overlaid raw data

165x165mm (300 x 300 DPI)

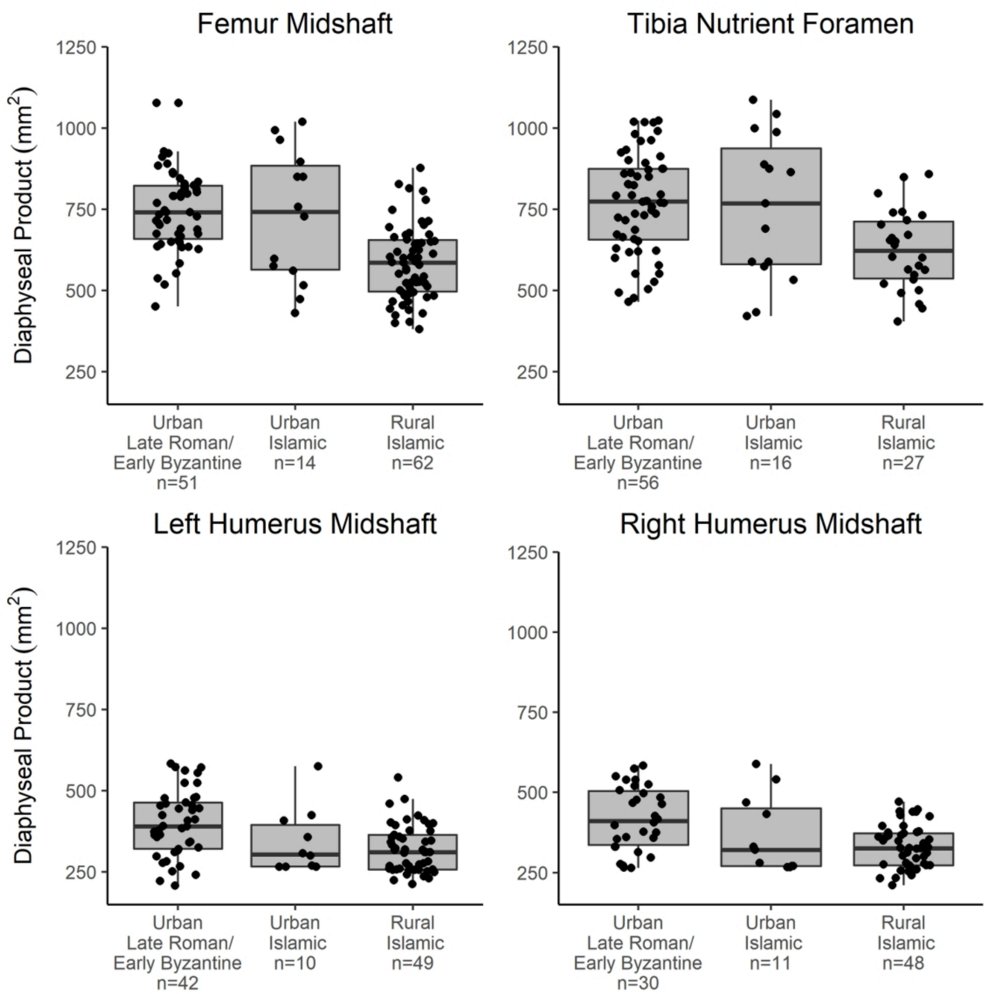

Figure 2: Boxplots of diaphyseal products with overlaid raw data

165x165mm (300 x 300 DPI)

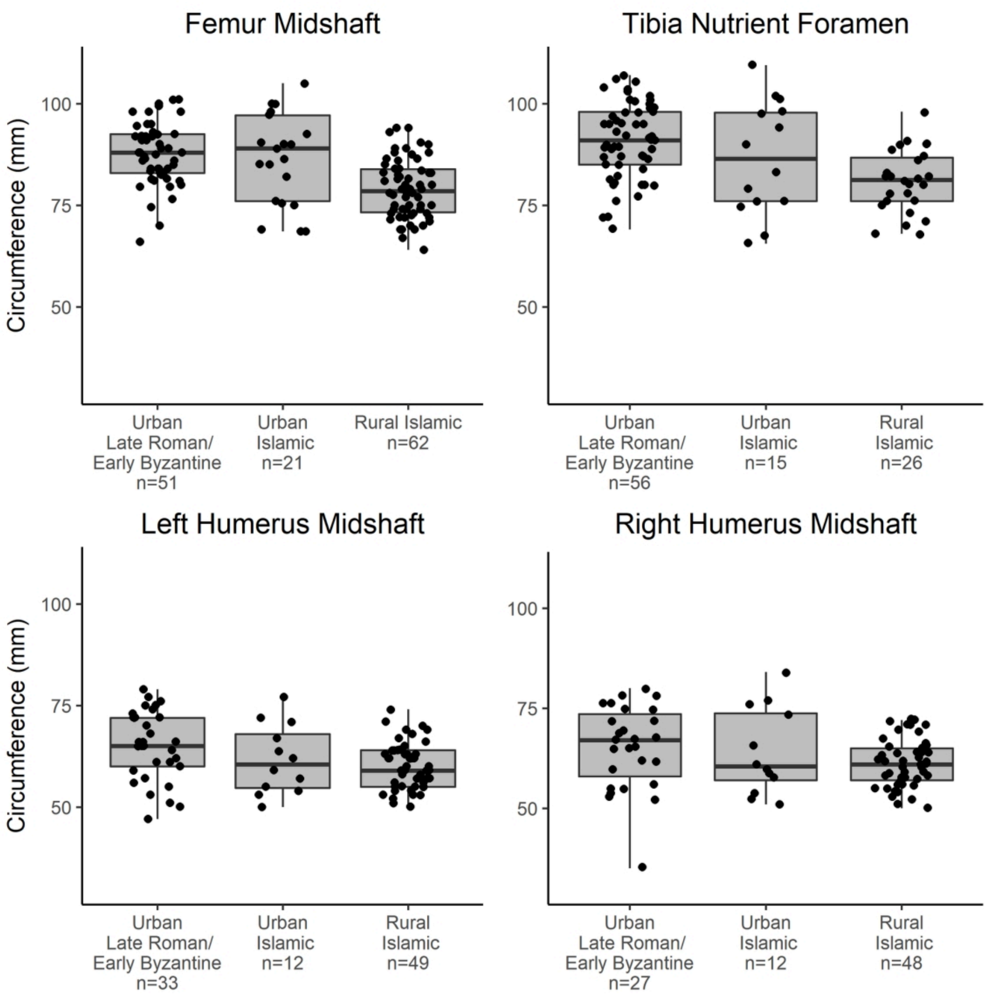

Figure 3: Boxplots of diaphyseal circumferences with overlaid raw data

165x165mm (300 x 300 DPI)

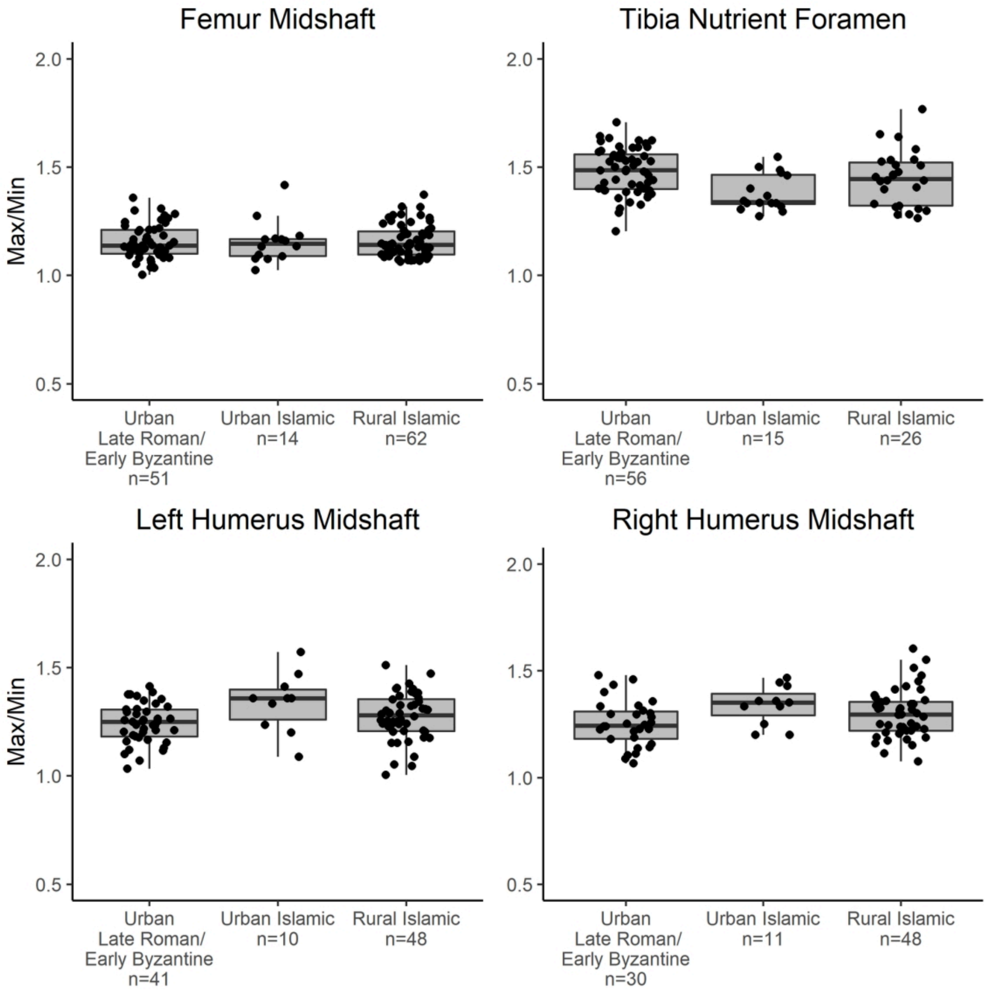

Figure 4: Boxplots of diaphyseal shape ratios with overlaid raw data

165x165mm (300 x 300 DPI)

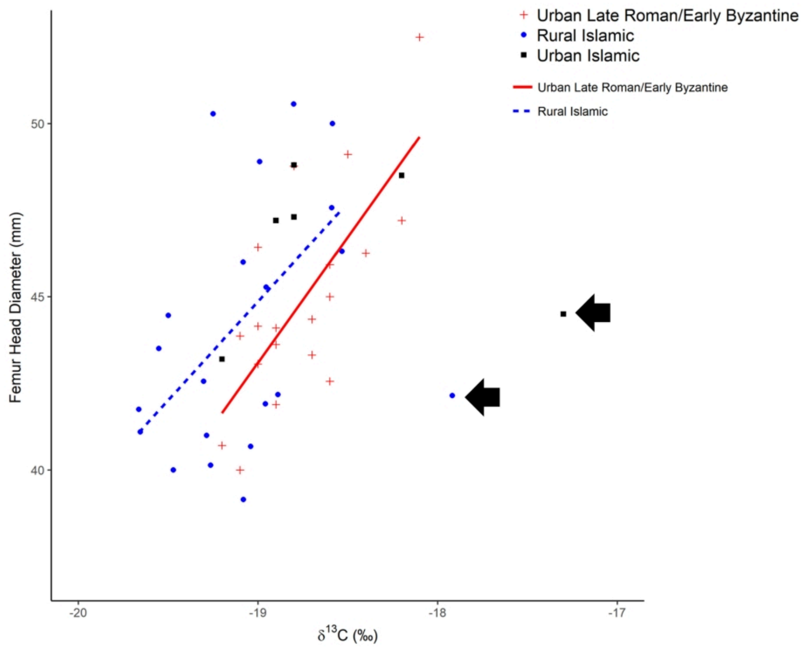

Figure 5: Scatterplot of femur head diameter regressed on δ13C with group specific regression lines (Outliers marked with arrows)

253x190mm (300 x 300 DPI)

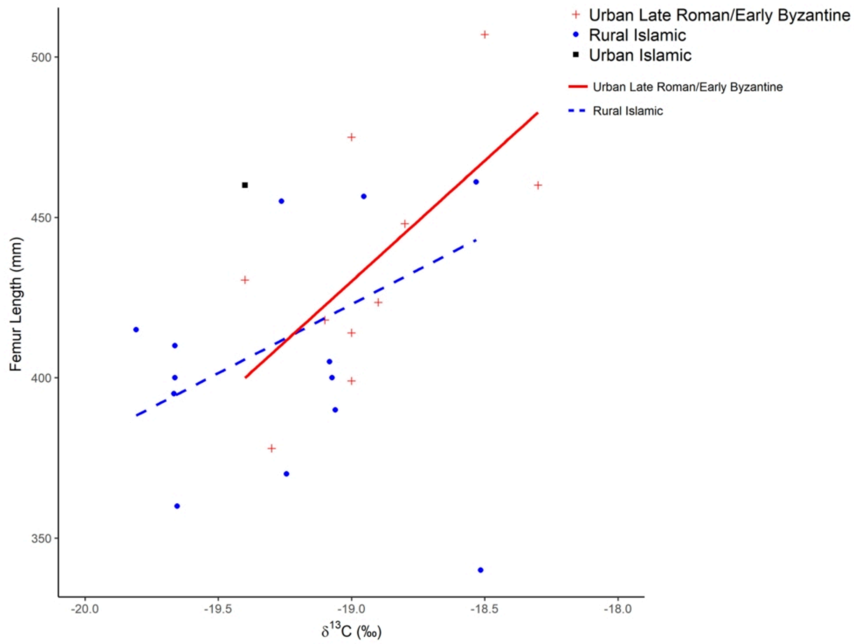

Figure 6: Scatterplot of femur length regressed on δ13C with group specific regression lines

253x190mm (300 x 300 DPI)

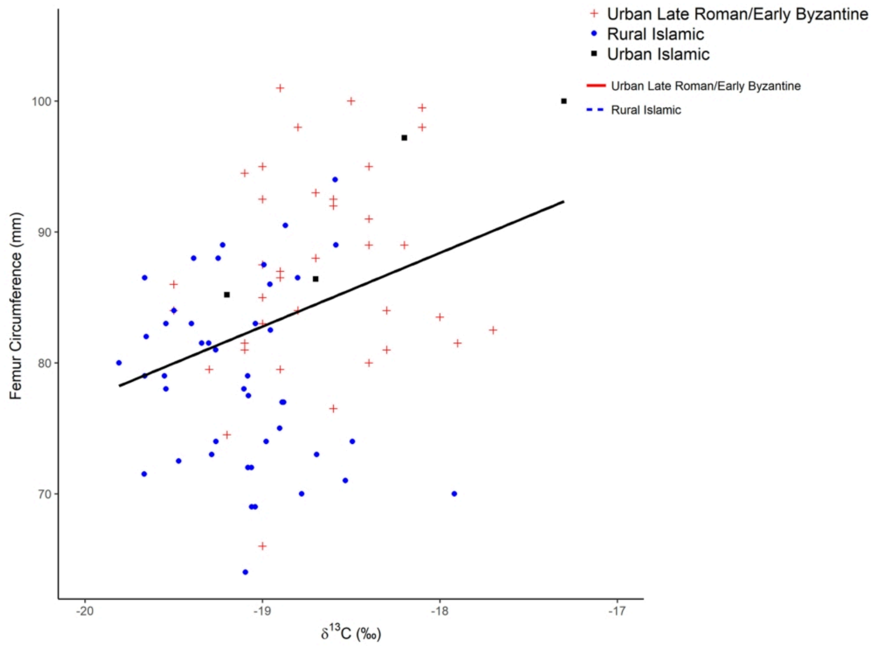

Figure 7: Scatterplot of femoral circumference regressed on δ13C. Only whole sample regression line shown, as archaeological period specific regressions non-significant

253x190mm (300 x 300 DPI)

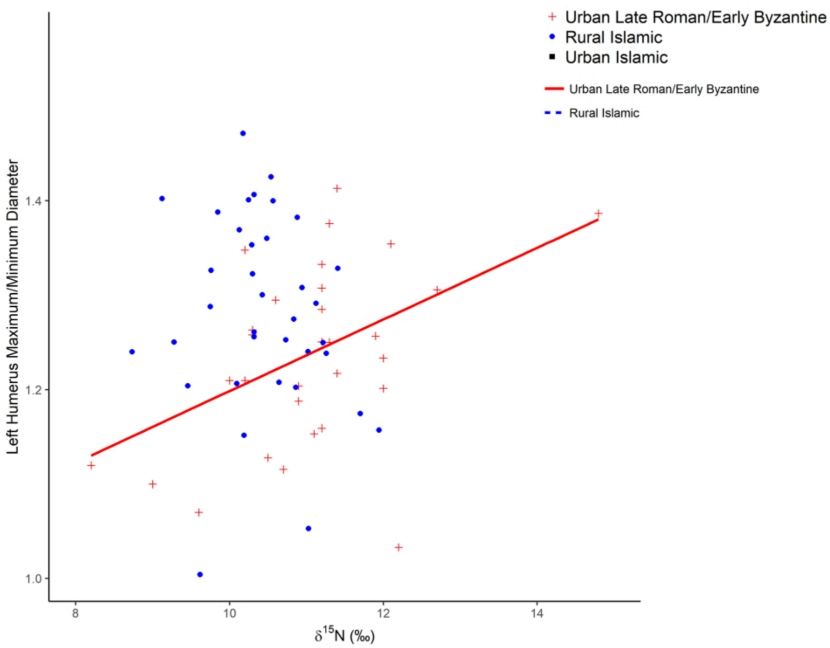

Figure 8: Scatterplot of left humerus maximum/minimum diameter ratio regressed on δ15N with Late Roman/ Early Byzantine period regression line.

253x190mm (300 x 300 DPI)